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# INVESTIGATION OF THERMAL PROCESSES IN GAS-THERMAL SPRAYING OF METAL-CERAMIC COATINGS

**A. V. Alifanov, V. M. Golub, and V. V. Alekhnovich**

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*The features of the thermal regime of gas-thermal deposition of metal-ceramic coatings have been studied. The procedure of calculation of the temperature field of a multicomponent coating throughout the process of formation has been developed. The quantitative dependences of the character of heating of the deposited particles and melting of the substrate on the thermophysical properties and chemical composition of the material, the intensity of heat exchange, and the technological parameters of the process have been established. The thermal conditions of spraying of powder compositions, which ensure improved strength characteristics of the coating–substrate system, have been determined.*

The process of application of metal-ceramic coatings under the conditions of gas-thermal spraying is a complex set of phenomena dissimilar in their physical, chemical, and thermodynamic content and interacting with each other throughout the production cycle. To efficiently investigate the features of their formation one must set apart the basic phenomena from all the phenomena occurring during the process and, having studied them, establish the necessary interrelations between different technological parameters.

An analysis shows that in most cases one of the dominant roles in gas-thermal spraying of coatings is played by thermal processes. A study of heat-exchange phenomena enables one to establish the basic dependences between different processes and to develop efficient methods of determination of the optimum regimes of spraying. A characteristic feature of the process under study is that the mutual thermal influence of particles in their heating and dynamic action on the substrate is excluded. This makes it possible to largely simplify a theoretical scheme of analysis of the interaction of the particle with the substrate and the gas flow.

Highly diverse mixtures of metal and ceramic powders which have different thermophysical properties and variously interact with the gas flow and the substrate in the thermal aspect are usually employed for spraying of metal-ceramic coatings. In theoretical analysis, the influence of the composition of a coating on the process of heat exchange can approximately be allowed for by the effective thermophysical coefficients allowing for the individual properties of specific components and their relative content in the material. In some cases, in analyzing the formation of metal-ceramic coatings, it becomes necessary to consider the features of the heat exchange of each component of the material applied.

In formation of coatings under the conditions of gas-thermal spraying of powder materials, one recognizes the thermal interaction of the powder particles with the gas flow and the substrate. These processes largely determine the strength properties and structure of the material sprayed.

The initial stage of formation of a coating in gas-thermal spraying of a powder is the process of thermal interaction between the material applied and the gas flow. In the general case we have the warmup, melting, spheroidization, and cooling of powder particles. The course of the thermal processes is greatly affected by the thermophysical properties of the material applied and by the configuration, structure, size, and character of movement of the particles in the gas flow.

Powder materials of different kinds have gained wide acceptance in production of metal-ceramic coatings under the conditions of gas-flame spraying. Powder particles are introduced into a gas flow conveying them to the

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Physical-Technical Institute, National Academy of Sciences of Belarus, 10 Kuprevich Str., Minsk, 220141, Belarus.
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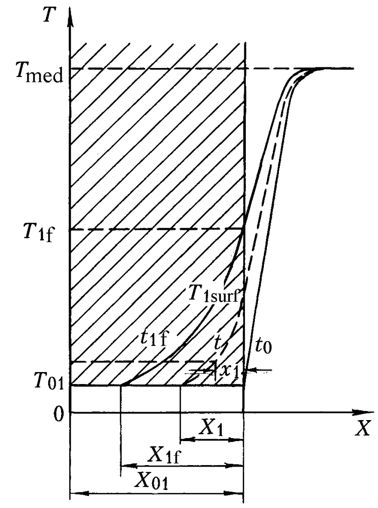


Fig. 1. Diagram of distribution of the temperature in the particle–gas flow system.

base. To determine the features of the thermal interaction of the particles with the gas flow one must establish the character of change of the temperature field of the particle–ambient medium system throughout the process, beginning with the instant of introduction of a particle into the gas flow and ending with the instant of its contact with the substrate. We will assume that the particle has a spherical shape and moves in a gas flow of constant temperature. In actual fact, the velocity of the flow is higher than the velocity of motion of the particles. Furthermore, the temperature of the gas flow decreases as it approaches the substrate. For calculations we must employ the average temperature on a certain portion of the flow whose length can be as small as is wished. The change in the flow temperature will be very slight on this portion and we can take a constant value of the temperature. In solving the problem, we also take the thermophysical coefficients of the particles to be known and constant. The influence of the composition of the material on the value of these coefficients is allowed for by employment of their effective values calculated according to the additivity rule. We consider further the features of heating of the particles to the fusion temperature, which is the most characteristic of the process of spraying of ceramic materials.

The process of heating of a particle begins with the instant of its introduction into the gas flow and ends when the particle surface attains the temperature of fusion of the material $T_{1f}$. The duration of the stage is $t_{1f}$; the depth of warmup at the instant $t = t_{1f}$ attains $X_{1f}$. During this process, the thermal front propagates from the surface deep into the particle (Fig. 1).

To determine the regularities of change of the temperature field of a spherical particle we use the method of elimination of variables [1]. With the aim of reducing the number of independent variables we assume the temperature distribution over the cross section of the particle in the form of a parabola of $n_1$th order:

$$T_1 = T_{01} + (T_{1surf} - T_{01}) \left(1 - \frac{x_1}{X_1}\right)^{n_1} . \tag{1}$$

To establish the character of change of the temperature distribution in the particle it is necessary to set up a differential heat-balance equation which must combine the quantity of heat $dQ_{1\alpha}$ supplied to the particle surface from the gas flow over the period $dt$, the quantity of heat $dQ_{1h}$ removed from (lost by) the surface by heat conduction over the same period $dt$, and the quantity of accumulated heat $dQ_{1ac}$, i.e.,

$$dQ_{1\alpha} = dQ_{1h} = dQ_{1ac} . \tag{2}$$

The quantity $dQ_{1\alpha}$ is determined according to the Newton law [1]

$$dQ_{1\alpha} = \alpha_1 (T_{med} - T_{1surf}) F_p dt , \tag{3}$$

and $dQ_{1h}$ is found from the Fourier law of heat conduction [1] and for a parabolic temperature distribution in the particle is equal to

$$dQ_{1h} = n_1 \frac{\lambda_1}{X_1} (T_{1surf} - T_{01}) F_p dt \,. \tag{4}$$

Having compared the obtained quantities of heat $dQ_{1\alpha}$ and $dQ_{1h}$, we find the dependence of the depth of the warmed-up particle layer on the temperature:

$$X_1 = n_1 \frac{\lambda_1}{\alpha_1} \frac{T_{1surf} - T_{01}}{T_{med} - T_{1surf}} \,. \tag{5}$$

The expression for the quantity element of accumulated heat, obtained on condition that the average integral temperature [1] and relation (5) are employed, has the form

$$dQ_{1ac} = \frac{n_1}{n_1 + 1} \frac{b_1^2}{\alpha_1} F_p \frac{T_{1surf} - T_{01}}{(T_{med} - T_{1surf})^2} \left[ 2T_{med} - T_{1surf} - \frac{2n_1}{(n_1 + 1) f_1} \frac{T_{1surf} - T_{01}}{T_{med} - T_{1surf}} (3T_{med} - T_{1surf}) + \right.$$

$$\left. + \frac{2}{(n_1 + 2)(n_1 + 3)} \left( \frac{n_1}{f_1} \right)^2 \left( \frac{T_{1surf} - T_{01}}{T_{med} - T_{1surf}} \right)^2 (4T_{med} - T_{1surf}) \right] dT_{1surf} \,. \tag{6}$$

where $f_1 = \alpha_1 X_{01}/\lambda_1$ and $b_1 = \sqrt{\lambda_1 \gamma_1 c_1}$.

Having substituted the values of $dQ_{1\alpha}$ and $dQ_{1ac}$ from (3) and (6) for the corresponding quantities into Eq. (2) and having integrated it from $t_0$ to $t$ and from $T_{01surf}$ to $T_{1surf}$, we obtain the time dependence of the particle-surface temperature:

$$t - t_0 = A_1 \left[ \left( \frac{T_{med} - T_{01}}{T_{med} - T_{1surf}} \right)^2 - \left( \frac{T_{med} - T_{01}}{T_{med} - T_{01surf}} \right)^2 \right] + A_2 \left[ \left( \frac{T_{med} - T_{01}}{T_{med} - T_{1surf}} \right)^3 - \left( \frac{T_{med} - T_{01}}{T_{med} - T_{01surf}} \right)^3 \right] +$$

$$+ A_3 \left[ \left( \frac{T_{med} - T_{01}}{T_{med} - T_{1surf}} \right)^4 - \left( \frac{T_{med} - T_{01}}{T_{med} - T_{01surf}} \right)^4 \right] + A_4 \ln \frac{T_{med} - T_{1surf}}{T_{med} - T_{01surf}} \,, \tag{7}$$

where

$$A_1 = \frac{n_1}{2(n_1 + 1)} \left( \frac{b_1}{\alpha_1} \right)^2 \left\{ 1 + 6 \left[ \frac{n_1}{(n_1 + 2) f_1} + \frac{3}{(n_1 + 2)(n_1 + 3)} \left( \frac{n_1}{f_1} \right)^2 \right] \right\} ;$$

$$A_2 = -\frac{4}{3} \frac{n_1}{n_1 + 1} \left( \frac{b_1}{\alpha_1} \right)^2 \left[ \frac{n_1}{(n_1 + 2) f_1} + \frac{4}{(n_1 + 2)(n_1 + 3)} \left( \frac{n_1}{f_1} \right)^2 \right] ;$$

$$A_3 = \frac{3}{2} \frac{n_1}{n_1 + 1} \left( \frac{b_1}{\alpha_1} \right)^2 \frac{1}{(n_1 + 2)(n_1 + 3)} \left( \frac{n_1}{f_1} \right)^2 ;$$

$$A_4 = \frac{n_1}{n_1 + 1} \left( \frac{b_1}{\alpha_1} \right)^2 \left\{ 1 + \frac{2n_1}{(n_1 + 2) f_1} \left[ 1 + \frac{n_1}{(n_1 + 3) f_1} \right] \right\} .$$

Expressions (1) and (7) enable us to find the temperature distribution in the particle in warming it up in the gas flow to the instant of the beginning of fusion.

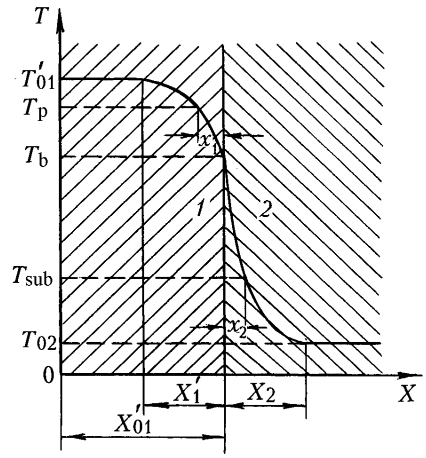


Fig. 2. Diagram of distribution of the temperature in the particle–substrate system: 1 and 2) material of the particle and the substrate.

The duration of warming-up of the particle to the beginning of fusion $t_{1f}$ is found from relation (7) with the conditions $t_0 = 0$, $T_{01surf} = T_{01}$, and $T_{1surf} = T_{1f}$. We have

$$t_{1f} = A_1\left(\frac{T_{med} - T_{01}}{T_{med} - T_{1f}}\right)^2 + A_2\left(\frac{T_{med} - T_{01}}{T_{med} - T_{1f}}\right)^3 + A_3\left(\frac{T_{med} - T_{01}}{T_{med} - T_{1f}}\right)^4 + A_4 \ln\frac{T_{med} - T_{1f}}{T_{med} - T_{01}}. \quad (8)$$

The depth of the warmed-up particle layer at the instant of the beginning of its fusion is determined from (5) on condition that $T_{1surf} = T_{1f}$:

$$X_{1f} = n_1 \frac{\lambda_1}{\alpha_1}\frac{T_{1f} - T_{01}}{T_{med} - T_{1f}}. \quad (9)$$

In calculating the process of thermal interaction of the particle with the gas flow, such parameters as the rate of change of the temperature and the velocity of advance of the front of warming-up of the particle are gaining in importance. The first quantity is determined from (7), whereas the second quantity is determined from (5).

The formulas obtained enable us to investigate the features of the process of heating of powder particles in the gas flow until their surface attains the temperature of fusion of the material, which is characteristic of the gas-thermal spraying of ceramic powder materials.

Let us consider the features of the thermal interaction between powder particles and the substrate.

The conditions of heat exchange at the boundary of contact of the particles of the sprayed powder and the substrate largely determine the quality and strength of cohesion between the coating and the base. In interaction of the sprayed substance with the base, in the general case we have deformation of the powder particles with their subsequent cooling. A local heating of the substrate immediately beyond the boundary of its contact with a particle is observed. It has been established experimentally [2, 3, and others] that in spraying onto a smooth surface the particles acquire the shape of a cylinder with a height-to-diameter ratio of 0.01–0.05, i.e., thermally a particle deformed in interaction with the substrate represents an infinite plane plate. On the other hand, in most cases the base has a thickness much larger than the transverse dimensions of a particle and, in solving the thermal problem, we can consider it as a semiinfinite body.

The analysis of the formation of different coatings has made it possible to establish that each particle is heated, deformed, and cooled strictly individually even with a maximum productivity of the process of spraying [2]. The probability of their mutual thermal influence is virtually absent.

Thus, when the thermal regime of interaction of particles with the base in formation of a coating under the conditions of gas-thermal spraying is considered, the problem is actually reduced to analysis of the distribution of the temperature field in the individual particle–base system. The particle deformed can realistically be considered as an infinite plate (plane wall), whereas the base can be considered as a semiinfinite body.

It is necessary to determine the temperature field of the particle–substrate system during the process of their thermal interaction. In the initial period, the particle represents a volume of a material with temperature $T'_{01}$ and thickness $X'_{01}$, which is bounded only in the transverse direction (Fig. 2). The initial temperature of the base is $T_{02}$. The problem will be solved on condition that the thermophysical coefficients of the system and the fusion temperature of the material are constant and that the temperature distribution in the particle and the base is parabolic [4]. Different cases of thermal interaction between the particle and the base occur depending on the regime of spraying and the physicomechanical properties of the material of the system's components. The most characteristic is the process during which the components of the system are in a solid state.

One basic parameter determining the character of formation of a coating in spraying is the temperature at the boundary of contact of the particle and the base (substrate) $T_b$. Let us consider the process of thermal interaction of the particle with the base with no change of their aggregate state (Fig. 2).

For the parabolic temperature distribution in the particle and the substrate the system of differential equations of heat balance of the process has the form

$$\frac{1}{n_1+1}\gamma_1 c_1 (T'_{01}-T_b)\, dX'_1 = n_1 \frac{\lambda_1}{X'_1}(T'_{01}-T_b)\, dt\,, \tag{10}$$

$$n_1 \frac{\lambda_1}{X'_1}(T'_{01}-T_b)\, dt = n_2 \frac{\lambda_2}{X_2}(T_b-T_{02})\, dt\,, \tag{11}$$

$$n_2 \frac{\lambda_2}{X_2}(T_b-T_{02})\, dt = \frac{1}{n_2+1}\gamma_2 c_2 (T_b-T_{02})\, dX_2\,. \tag{12}$$

Carrying out separation of variables, certain transformations, and integration of Eqs. (10) from 0 to $t$ and from 0 to $X'_1$, we obtain the time dependence of the depth of the cooled particle layer:

$$X'_1 = \sqrt{2n_1 (n_1+1)\frac{\lambda_1}{\gamma_1 c_1} t}\,. \tag{13}$$

Analogously we find from (12) the depth of the warmed-up substrate layer:

$$X_2 = \sqrt{2n_2 (2n_2+1)\frac{\lambda_2}{\gamma_2 c_2} t}\,. \tag{14}$$

By simultaneous solution of (11), (13), and (14), we obtain the dependence for determination of the temperature at the boundary of contact of the particle and the substrate:

$$T_b = \frac{b_1 T'_{01} + m b_2 T_{02}}{b_1 + m b_2}\,, \tag{15}$$

where $b_2 = \sqrt{\lambda_2\gamma_2 c_2}$ and $m = \sqrt{\frac{n_2(n_1+1)}{n_1(n_2+1)}}$.

Expression (15), on condition that $n_1 = n_2$, is reduced to the relation for determination of the temperature of ideal contact of two bodies [4]. As follows from (15), the quantity $T_b$ remains constant throughout the process of ad-

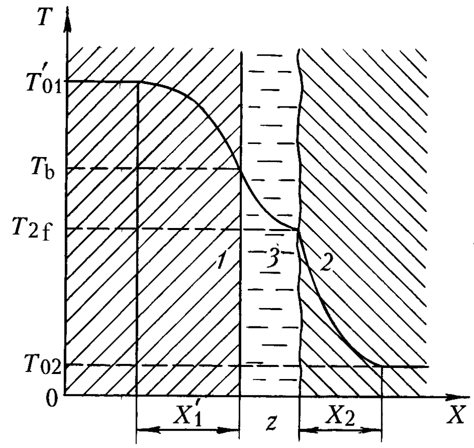


Fig. 3. Diagram of distribution of the temperature in the particle–substrate system in melting of the substrate material: 1 and 2) material of the particle and the substrate; 3) molten material of the substrate.

vance of the cooling front to the interior surface of the particle and is directly dependent on the thermophysical characteristics and the initial values of the temperatures of the system's components.

When the value of the quantity $T_b$ is known, the temperature distribution in the particle is determined from the expression

$$T_p = T'_{01} - (T'_{01} - T_b)\left(1 - \frac{x_1}{X'_1}\right)^{n_1} \tag{16}$$

and accordingly in the substrate it is determined from

$$T_{sub} = T_{02} + (T_b - T_{02})\left(1 - \frac{x_2}{X_{02}}\right)^{n_2} . \tag{17}$$

The formulas (15)–(17) obtained enable us to determine the temperature field of the particle–substrate system during the basic period of formation of coatings.

For the case of thermal interaction of the particle with the substrate under the conditions of melting of the base material, which is observed in spraying of high-temperature ceramic powders onto a metal substrate (Fig. 3), the equation of heat balance of the process has the form

$$\frac{1}{n_1 + 1}\gamma_1 c_1 (T'_{01} - T_b) X'_1 = \gamma'_2 r_f z + \gamma_2 c_2 (T_{2f} - T_{02}) z +$$

$$+ \frac{1}{n'_2 + 1}\gamma'_2 c'_2 (T_b - T_{2f}) z + \frac{1}{n_2 + 1}\gamma_2 c_2 (T_{2f} - T_{02}) X_2 . \tag{18}$$

To solve Eq. (18) we must establish additional relations between the variables $X'_1$, $T_b$, $X_2$, and $z$. This will be carried out as follows.

From the condition of heat exchange at the boundary of contact of the particle and the substrate with allowance for the transfer of heat in a thin molten layer only by heat conduction [5], the differential heat-balance equation can be represented as

$$n_1 \frac{\lambda_1}{X'_1}(T'_{01} - T_b)\, dt = n'_2 \frac{\lambda'_2}{z}(T_b - T_{2f})\, dt . \tag{19}$$

Solution of Eq. (19) yields the dependence of the molten-layer thickness on the quantity $T_b$ and the depth of the cooled region of the particle:

$$z = \frac{n_2' \lambda_2'}{n_1 \lambda_1} \frac{T_b - T_{2f}}{T_{01}' - T_b} X_1' . \tag{20}$$

Having substituted the values of $X_1'$, $z$, and $X_2$ from (13), (20), and (14) for the corresponding quantities into Eq. (18) and having carried out certain transformations, we obtain the dependence for determination of the temperature at the boundary of contact of the particle and the base:

$$T_b = \left\{ \frac{2n_2'}{n_2' + 1} b_2^2 T_{2f} + n_1 \lambda_1 \frac{\gamma_2 c_2}{n_2 + 1} (T_{2f} - T_{02}) \sqrt{\frac{n_2 (n_2 + 1) a_2}{n_1 (n_1 + 1) a_1}} + \frac{2n_1}{n_1 + 1} b_1^2 T_{01}' - \right.$$

$$- n_2' \lambda_2' [\gamma_2' r_f + \gamma_2 c_2 (T_{2f} - T_{02})] + \left\{ \left\{ \frac{2n_2'}{n_2' + 1} b_2'^2 T_{2f} + n_1 \lambda_1 \frac{\gamma_2 c_2}{n_2 + 1} (T_{2f} - T_{02}) \sqrt{\frac{n_2 (n_2 + 1) a_2}{n_1 (n_1 + 1) a_1}} + \right. \right.$$

$$\left. + \frac{2n_1}{n_1 + 1} b_1^2 T_{01}' - n_2' \lambda_2' [\gamma_2' r_f + \gamma_2 c_2 (T_{2f} - T_{02})] \right\}^2 + 4 \left[ \frac{n_2'}{n_2' + 1} b_2'^2 - \frac{n_1}{n_1 + 1} b_1^2 \right] \times$$

$$\times \left\{ \frac{n_2'}{n_2' + 1} b_2'^2 T_{2f}^2 - n_2' \lambda_2' [\gamma_2' r_f + \gamma_2 c_2 (T_{2f} - T_{02})] T_{2f} + n_1 \lambda_1 \frac{\gamma_2 c_2}{n_2 + 1} (T_{2f} - T_{02}) \times \right.$$

$$\left. \left. \left. \times \sqrt{\frac{n_2 (n_2 + 1) a_2}{n_1 (n_1 + 1) a_1}} T_{01}' - \frac{n_1}{n_1 + 1} (b_1 T_{01}')^2 \right\} \right\}^{1/2} \right\} \frac{1}{2} \left[ \frac{n_2'}{n_2' + 1} b_2'^2 - \frac{n_1}{n_1 + 1} b_1^2 \right]^{-1} , \tag{21}$$

where $b_2' = \sqrt{\lambda_2' \gamma_2 c_2'}$.

Expression (21) enables us to calculate the temperature at the boundary of contact of the particle and the substrate under the conditions of its melting. When the value of $T_b$ is known, it is easy to determine the values of $X_1'$, $X_2$, and $z$ and the temperature field of the system from relations (13)–(17) and (20).

In formation of metal-ceramic coatings, one uses a mixture of ceramic and metal powders as a material for gas-thermal spraying, which determines the characteristic thermal conditions in the process of interaction of the particles with the substrate. The temperature field in a metal-ceramic coating can approximately be determined with the use of the regularities obtained and the values of the effective thermophysical coefficients of the material of the particles sprayed. For example, the density of a metal-ceramic material can be determined by the relation [6]

$$\gamma_{ef} = \gamma_c V_c + \gamma_{met} (1 - V_c) , \tag{22}$$

the specific heat determined by

$$c_{ef} = c_c P_c + c_{met} (1 - P_c) , \tag{23}$$

and the thermal-conductivity coefficient found from [7]:

$$\lambda_{ef} = \lambda_{met} \left( 1 + \frac{V_c}{(1 - V_c)/3 + \lambda_{met}/(\lambda_c - \lambda_{met})} \right). \tag{24}$$

Under the conditions of spraying of metal-ceramic materials, in calculation of the temperature field from the formulas derived, instead of the quantities $\lambda_1$, $c_1$, and $\gamma_1$ it is necessary to employ their effective values from (22)–(24).

Thus, the analysis made enables us to approximately evaluate the thermal regime of formation of metal-ceramic coatings under the conditions of gas-thermal spraying and to correctly approach the selection of the most rational technological parameters of the process.

## NOTATION

$a_1$ and $a_2$, coefficients of thermal diffisuvity of the particle and substrate materials, m$^2$/sec; $c_1$, $c_2$, and $c_2'$, specific heats of the materials of the particle and the solid and liquid substrate, J/(kg·deg); $c_c$, $c_{met}$, and $c_{ef}$, specific heat of the ceramic material, the metal, and their mixture, J/(kg·deg); $F_p$, area of the particle surface, m$^2$; $F_b$, area of contact of the particle and the substrate, m$^2$; $n_1$, $n_2$, and $n_2'$, exponents of parabolicity of the curve of temperature distribution in the particle, the substrate, and the molten substrate material; $P_c$, relative mass content of ceramics in the material; $Q_{1\alpha}$, $Q_{1h}$, and $Q_{1ac}$, transferred, removed, and accumulated heat, J; $r_f$, specific heat of fusion of the substrate, J/kg; $T_{01}$ and $T_1$, initial and running temperature of the particle, $^oC$; $T_{01surf}$ and $T_{1surf}$, initial and running surface temperature of the particle, $^oC$; $T_{med}$, temperature of the medium (gas flow), $^oC$; $T_{01}'$ and $T_{02}$, values of the temperatures of the particle and the substrate at the initial instant of contact, $^oC$; $T_{1f}$ and $T_{2f}$, fusion temperature of the particle and substrate material, $^oC$; $T_p$, $T_{sub}$, and $T_b$, running temperatures of the particle, the substrate, and the region of the boundary during their interaction, $^oC$; $t$, time, sec; $t_{1f}$, time of attainment of the fusion temperature by the particle surface, sec; $V_c$, relative volume content of ceramic inclusions in the material; $X_{01}$, particle radius, m; $X_1$ and $X_{1f}$, running depth of warmup of the particle and depth of its warmup at the instant of attainment of the fusion temperature by the surface, m; $X_{01}'$, initial thickness of the particle at the instant of its interaction with the substrate, m; $X_1'$ and $X_2$, depth of the cooled layer of the particle and the warmed-up layer of the substrate during their interaction, m; $x_1$ and $x_2$, coordinates reckoned from the surface of the particle and the substrate in depth, m; $z$, thickness of the molten substrate layer, m; $\alpha_1$, coefficient of heat transfer from the particle surface, W/(m$^2$·deg); $\gamma_1$, $\gamma_2$, and $\gamma_2'$, densities of the materials of the particle and the solid and liquid substrate, kg/m$^3$; $\gamma_c$, $\gamma_{met}$, and $\gamma_{ef}$, densities of the ceramic materials, the metal, and their mixture, kg/m$^3$; $\lambda_1$, $\lambda_2$, and $\lambda_2'$, coefficients of thermal conductivity of the particles and the solid and liquid substrate, W/(m·deg); $\lambda_c$, $\lambda_{met}$, and $\lambda_{ef}$, coefficients of thermal conductivity of the ceramic material, the metal, and their mixture, W/(m·deg). Subscripts: ac, accumulation; b, boundary; c, ceramics; met, metal; sub, substrate; surf, surface; f, fusion; med, medium; h, heat conduction; p, particle; ef, effective; 0, initial values of the quantities; 1, sprayed material; 2, substrate.

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